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VLA Observations of Three M 33 Supernova Remnants at 20 cm

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Abstract. Three supernova remnants (SNR) have been mapped in the galaxy M33 with the Very Large Array* (VLA) at 20 cm. The angular resolution is ~ 1.3 arcsec or ~ 4 pc at a distance of 600 kpc and the rms noise is ~ 0.04 mJy /beam. One of the radio sources shows evidence for a shell structure with a size of ~ 15 pc, confirming the SNR nature of this source. The second object is extended and may well be a thick-shell SNR of size ~ 12 pc. The third object is a small, presumably young SNR with a size of ~ 4 pc.

Key words: supernova remnants, radio observations — external galaxies, individual — radio sources, VLA observations

1. Introduction

Radio investigations of conventional supernova remnants (SNR) in nearby galaxies are only possible within the local group of galaxies. Extensive investigations of the SMC and LMC have recently been completed with the Molonglo Observatory Synthesis Telescope (MOST) at 843 MHz with a resolution of ~ 43 arcsec (~ 10 pc) (Mills 1983; Mills & Turtle 1984; Mills *et al.* 1984). In M 31 and M 33, the radio emission from SNR is quite weak. As an example, an intense young galactic SNR such as Tycho (3C 10; 43 Jy at a distance of ~ 4 kpc) would have a flux density of only ~ 2 mJy at a distance of 600 kpc corresponding to the distance of M 33 (Humphreys 1980). A radio survey of M 31 SNR using the VLA has been carried out by Dickel *et al.* (1982), who detected five SNR at 20 cm with flux densities in the range 1 to 3.4 mJy. In addition, Dickel & D’Odorico (1984) have determined the non-thermal nature of several of the SNR in M 31 based on 6 cm VLA observations.

The directed radio observations of M 33 SNR began with observations by Goss *et al.* (1980, GEDI) of three of the SNR previously found in an optical survey by D'Odorico, Benvenuti & Sabbadin (1978) and confirmed to be SNR by spectroscopic studies of Danziger *et al.* (1979). These three (SN-1, 2, 3) were detected in a 21 cm continuum Westerbork Synthesis Radio Telescope (WSRT) map. Two of the objects (SN-2,3) were detected at 6 cm with maps made with the partially completed VLA in 1978 (resolution

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~ 1.5 arcsec and rms noise ~ 0.25 mJy /beam). Based on a more extensive optical survey of SNR in M 33 by D'Odorico, Dopita & Benvenuti (1980) (19 objects, DDB list), D'Odorico, Goss & Dopita (1982, DGD) looked for radio emission from these SNR using the WSRT at 21 cm. Five certain and three possible detections were reported, including the original three (SN-1, 2, 3). Viallefond *et al.* (1985) have also investigated the radio properties of the faint, extended SNR candidate DDB-1 (size ~ 18 arcsec); a weak radio source of 0.8 ± 0.3 mJy was detected. Blair & Kirshner (1985) have confirmed the SNR nature of this source based on optical spectroscopic measurements.

We have used the VLA in the A-array at 20 cm with an angular resolution of ~ 1.3 arc sec (4 pc) and an rms noise six times more favourable than the 1978 VLA observations. Three of the objects studied by GEDI (SN-1 = DDB-7; SN-2 = DDB-8; SN-3 = DDB-9) were observed.

The purpose of these observations was to use the highest possible resolution and sensitivity to study the radio morphology of these SNR. In particular, these observations have revealed a shell structure for one of the SNR, and a possible shell structure for a second.

2. Observations

The three SNR in M 33 were observed on 1983 November 14 during a period of 12 hours. The observing frequencies were 1465 and 1515 MHz with a total of four 50 MHz bands in both senses of circular polarization. The angular resolution was ~ 1.3 arcsec. Each object was observed separately since the delay beam of the VLA in the A-array is ~ 1 arcmin and the sources have typical separations of 3–4 arcmin. The observing time per field ranged from 1.7 to 2.7 hours with rms noises in the range 0.04 to 0.03 mJy /beam (Table 1). The maps were 'cleaned' to correct for distortions due to sidelobes.

3. Results

The 20 cm maps of the objects DDB-7, 8 and 9 are shown in Figs 1, 2 and 3. In these maps 1 mJy/beam corresponds to ~ 330 K full beam brightness temperature Fig. 1(a) shows the SNR DDB-7 and 1 (b) shows the source D, 40 arcsec to the southwest. Source D is probably an extragalactic background source (Israel & van der Kruit 1974; Viallefond *et al.* 1985) as it has no optical counterpart in M 33. In addition, the radio morphology (Fig. 1b) suggests that it could be an extragalactic double (size ~ 3 arcsec) with an unequal flux density ratio between the two radio lobes.

The source parameters are summarized in Table 1. The positions for the extended sources refer to the centroid of the emission. The optical sizes in column 8 are taken from GEDI, DGD and Viallefond *et al.* (1985). Very uncertain values are indicated by(:).

The VLA flux densities at 20 cm given in Table 1 are less than the WSRT values at 21 cm (GEDI) by 3.1 ±1.0 mJy (source D), 0.4 ± 0.3 mJy (DDB-7), 2.9 ± 0.5 mJy (DDB-8) and 2.5 ± 0.5 mJy (DDB-9). This difference is probably due to confusion problems in the WSRT data. Source D, DDB-7 and DDB-9 are located in the

Table 1. 20 cm observations of M 33 sources.

Name	Type	Observing time hr	rms noise mJy/beam	α (1950)	δ (1950)	θ radio arcsec	θ Hα arcsec	S_{tot} mJy
				h m s s	° ′ ″ ″			
Source D*	BG**	2.1	0.042	01 30 39.65 ± 0.01	30 17 47.2 ± 0.1	< .3	...	9.4 ± 0.3
DDB-7	SNR	2.1	0.042	01 30 42.11 ± 0.01	30 18 11.1 ± 0.1	1.5	2.5†, < 2.5‡	1.3 ± 0.1
B 33	H II	2.7	0.038	01 30 45.7 ± 0.1	30 21 44 ± 1	3:	4§	1.0 ± 0.3
DDB-8*	SNR	2.7	0.032	01 30 46.79 ± .03	30 21 05.7 ± 0.3	~4	3.6†, 2.5‡	2.9 ± 0.2
...	...	2.7	0.038	01 30 47.95 ± .02	30 20 31.4 ± 0.2	< 1	...	0.4 ± 0.1
DDB-9	SNR	1.7	0.043	01 31 05.75 ± .03	30 17 49.3 ± 0.3	~5	3.3†, 3.2‡	4.5 ± 0.2

* Position and size refer to prominent peak. Flux density refers to entire source. ** BG = background source. † GEDI. ‡ DDB. § Viallefond *et al.* (1985).

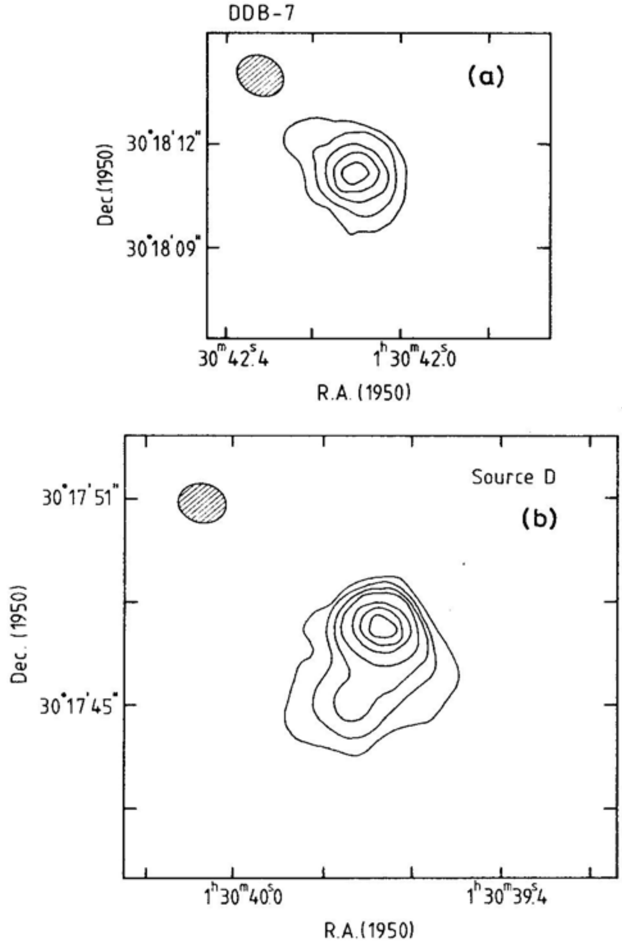

Figure 1. (a) DDB-7 (SN-1) at 20 cm as observed with the VLA in the A-array. The angular resolution is 1.38 arcsec × 1.18 arcsec at a position angle of 78°. The contour units are 0.1, 0.2, 0.3, 0.4, 0.5 mJy/beam. The rms noise is 0.042 mJy/beam. (b) Source D, to the southwest of DDB-7, a probable background source. The beamwidth is the same as for DDB-7 and the contour units are 0.2, 0.4, 0.6, 1,2,3,4 mJy/beam.

prominent, southern spiral arm of M 33 (Viallefond *et al.* 1985); at these low flux density levels (< 5 mJy), it is difficult to perform a precise separation of source emission from spiral arm emission. For DDB-8 the presence of nearby HII emission (see below) is a probable cause of confusion.

4. Discussion

Two of the detected SNR (DDB-8, 9) are clearly resolved with angular sizes in good agreement with the earlier 6 cm VLA observations and in reasonable agreement with the optical determinations (GEDI, DGD).

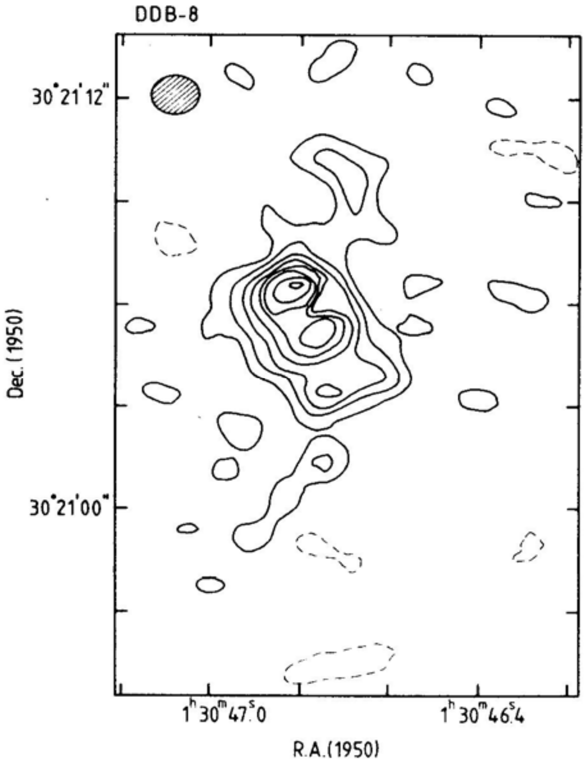

Figure 2. DDB-8(SN-2) at 20 cm. The beamwidth is 1.5 arcsec × 1.14 arcsec at position angle 87°. The contour units are – 0.06, 0.06, 0.12, 0.18, 0.24, 0.30, 0.36, 0.42, 0.48 mJy/beam. The rms noise is 0.032 mJy/beam.

The shell structure for DDB-9 (SN-3) suggested by GEDI is confirmed by the present data (Fig. 3) and is further evidence that this source is in fact a SNR. The shell size of ~ 5 arcsec corresponds to a diameter of 15 pc. By comparing with the results of GEDI, the rather flat spectral index of 0.2 ± 0.1 ($S \propto \nu^{-\alpha}$) is derived between 6 and 20 cm.

The object DDB-8 is a radio source with a complex morphology (Fig. 2). This morphology could be caused by thick shell structure with a size of ~ 4 arcsec or 12 pc. We cannot, however, exclude that some of the radio structure is caused by the crowding of several individual sources. D'Odorico, Benvenuti & Sabbadin (1978), DDB, and Danziger *et al.* (1979) remark on the presence of faint HII emission adjacent to DDB-8. The total emission from the radio source (above the 4 σ level) in Fig. 2 is 2.9 ± 0.2 mJy while the major radio source of flux density ~ 2.5 mJy has a position within 1.5 arcsec of the optical position of DDB-8 (DGD) and is thus probably related to the optical SNR. The weak emission (flux density ~ 0.4 mJy) 4–5 arcsec to the NW could be related to HII emission. Two other sources are also present in the DDB-8 field: 40 arcsec to the NW there is a source of 1.0 + 0.3 mJy (Table 1) which coincides with the H α nebula B 33 (Boulesteix *et al.* 1974). To the SE of DDB-8 there is an additional source (Table 1) which might be related to B1004; however the radio position is ~ 7 arcsec NE of the optical position and thus the identification is far from certain. In addition, the radio source is compact (< 1 arcsec) in contrast to the H α nebula (~ 12 arcsec). Thus,

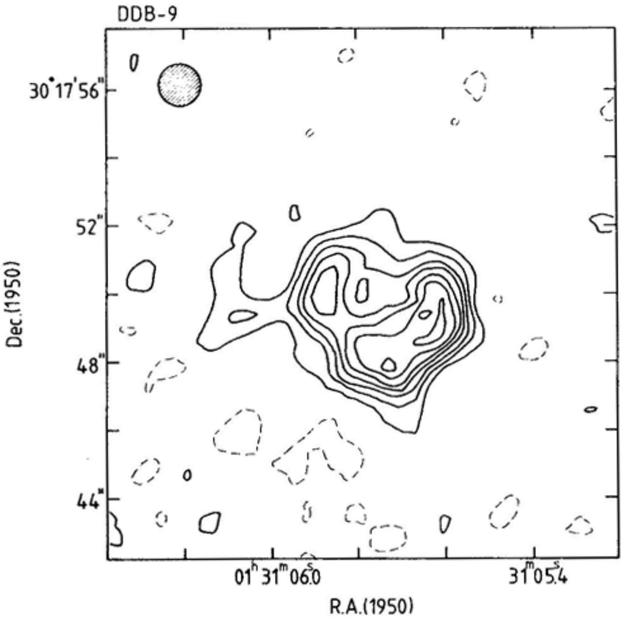

Figure 3. DDB-9 (SN-3) at 20 cm. The beamwidth is 1.28 arcsec x 1.15 arcsec at a position angle of 98°. The contour units are: – 0.08, 0.08, 0.16, 0.24, 0.32, 0.40, 0.48, 0.56 mJy/beam. The rms noise is 0.043 mJy/beam.

the WSRT 21 cm observation of DDB-8, which shows an extended source at position angle 150°, is affected by confusion arising from nearby HII regions. The spectral index of the major source in Fig. 2 can be derived using the 6 cm VLA data from GEDI and the 6 cm VLA data described by Viallefond *et al.* (1985); both results are in good agreement and indicate a spectral index between 6 and 20 cm of 0.0 ± 0.15. Thus the identification of DDB-8 as a SNR must rest entirely on the optical spectroscopy of Danziger *et al.* (1979), Dopita, D'Odorico & Benvenuti (1980) and Blair & Kirshner (1985).

The SNR DDB-7 is much more compact, with an optical size of 2.5 arcsec (GEDI) or < 2.5 arcsec (DGD) and a slightly extended radio source with a deconvolved size of 1.5 arcsec or 4 pc. This must be a young SNR with a surface brightness at 20 cm, Σ, of 300×10^{-21} W m^{-2} Hz sr^{-1}.

SNR in M 33 are faint radio sources. Even with the full sensitivity of the VLA, mapping large numbers of M 33 SNR is difficult. Of the 112 radio sources identified with H α nebulosities by Viallefond *et al.* (1985), only at most nine sources can be identified with SNR in the various optical catalogues. Thus a large fraction of the SNR have flux densities < 1 mJy and the HII catalogue of Viallefond *et al.* (1985) does not suffer from substantial SNR contamination. It is still clear that optical searches (DDB) and spectroscopic follow-up observations (*e.g.* Dopita, D'Odorico & Benvenuti 1980; Blair & Kirshner 1985) are the most efficient method to discover SNR in local group galaxies beyond the Magellanic Clouds. Radio observations are, however, useful in studying individual objects.

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